Higgs Self-Coupling at the ILC with the SiD Detector
(A Snowmass 2021 Leter of Interest)

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Abstract

Measuring the Higgs boson self-coupling λ_{hhh} with high precision is an important part of the program for particle physics in the coming decades. In the Standard Model (SM), $\lambda_{hhh}^{SM} = m_h^2/2v^2$ is determined by two parameters, $v = (\sqrt{2}G_F)^{1/2} \approx 246$ GeV and $m_h \approx 125$ GeV. In Beyond the SM (BSM) scenarios, new particles can enhance or diminish the self-coupling through mixing or in loops. In e^+e^- colliders λ_{hhh} is measured by measuring the cross section for double Higgs production $e^+e^- \to ZHH$ or $e^+e^- \to \nu\bar{\nu}HH$. In this study we investigate the expected sensitivity to λ_{hhh} at the ILC with the SiD detector.

Introduction

The potential for a model-independent determination of the Higgs boson self-coupling at an e^+e^- collider which achieves the threshold center of mass energy required for double Higgs boson production has been thoroughly investigated in [1]. The International Linear Collider (ILC) is one of two such colliders currently under consideration for construction by the international community. See Figure 1 for the Feynman diagrams for double Higgs production at an e^+e^- collider.

The importance of this measurement has been categorically asserted in the European Strategy briefing book [2] and the Higgs boson study from which it is informed [3]. The measurement is important not for verifying that the triple Higgs coupling λ_{hhh} conforms to the Standard Model (SM) prediction $\lambda_{hhh}^{SM} = m_h^2/2v^2$, but for testing if it does not. If it does not, then Beyond the SM (BSM) theories may explain why. Model specific modification of λ_{hhh} from mixing of a Higgs singlet, doublet, or triplet is investigated in [4], where it is found that BSM effects are considerably larger in λ_{hhh} than in the Higgs couplings to fermions and gauge bosons. Modification in supersymmetric models like the Minimal Supersymmetric SM (MSSM) and the Next to MSSM (NMSSM) are investigated, for example, in [5] and [6].

The Silicon Detector (SiD)

SiD was designed to carry out the physics program of the ILC. The intent of the SiD consortium was announced in the Letter of Intent [7] and a baseline design reported and evaluated in the Detailed

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Baseline Design (DBD) in the ILC Technical Design Report Volume 4 [8]. An SiD Snowmass 2021 Letter of Interest outlines the goals with respect to the APS DPF Snowmass process.

Briefly, SiD comprises compact tracking and calorimeter subdetectors designed to maximize particle flow technique performance within a 5T magnetic field. The vertex detector is a five layer structure instrumented with Silicon pixels for precise vertex determination, while the five layers of the tracker are instrumented with Silicon strips. The electromagnetic (hadronic) calorimeter alternates Tungsten (Steel) absorbing layers with Silicon pixel (Resistive Plate Chamber) sensitive layers. In full simulation, the tracking achieves $\delta(1/p_T) = 2 \times 10^{-5}$/GeV momentum resolution, while the calorimetry achieves $\Delta E/E = 0.01 \oplus 0.17/\sqrt{E}$ ($\Delta E/E = 0.094 \oplus 0.56/\sqrt{E}$) energy resolution in the electromagnetic (hadronic) calorimeter.

Studies at ILD and CLIC

Two full simulation studies with the International Large Detector (ILD) have been performed investigating the sensitivity to λ_{hhh} at the ILC. In [9], the authors studied double Higgsstrahlung $e^+e^- \to ZHH$ at $\sqrt{s} = 500$ GeV and double WW fusion at $\sqrt{s} = 1000$ GeV. In both cases signal events were separated into categories $Z \to \ell^+\ell^-, \nu\bar{\nu}, q\bar{q}$, fully covering the Z decays. In both cases the dominant double Higgs decay $HH \to b\bar{b}b\bar{b}$ was targeted for separating signal from background using neural networks to exploit b-tagging performance. In [10], the study focused on double Higgsstrahlung $e^+e^- \to ZHH$ at $\sqrt{s} = 500$ GeV using boosted decision trees. In both cases the dominant background was found to be $e^+e^- \to ZZH$, with a Z mimicking the H. With 2ab^{-1} integrated luminosity and 80% e^-_L, 30% e^+_R polarized beams, the former study expects 44% precision on the λ^{SM}_{hhh}, while with the same luminosity and polarization the latter study expects 49% precision.

The Compact Linear Collider (CLIC) study [11] uses full simulation to study the sensitivity at $\sqrt{s} =$ 1.4 TeV and $\sqrt{s} = 3.0$ TeV using both double Higgs production mechanisms at the former energy and only double WW fusion at the latter. In this case the double Higgs decays $HH \to b\bar{b}b\bar{b}$ and $HH \to b\bar{b}WW^\star$ are used to separate signal from background. With 0.7ab^{-1} integrated luminosity at $\sqrt{s} = 1.4$ TeV, the CLIC study expects $^{+36\%}_{-34\%}$ precision on λ^{SM}_{hhh} while including the higher energy measurement in combination with other Higgs coupling measurements the precision is significantly improved.

Questions to Investigate

The precision with which λ_{hhh} can be measured at SiD depends on ILC parameters and SiD detector design. Some questions which deserve further study follow:

- Current studies assume operating points at $\sqrt{s} = 500, 1000, 1500, 3000$ GeV. Is sensitivity improved at other $\sqrt{s}$? Are there $\sqrt{s}$ where background phase space enhances sensitivity?
- How sensitive is the ILC and SiD to particular double Higgs production benchmarks from BSM? What about Snowmass 2021 benchmarks?
- The $b\bar{b}\tau^+\tau^-$ channel has not been investigated. Can it help separate Z/H using polarization? How useful is the collinear approximation for $H \to \tau^+\tau^-$ reconstruction?
- As τ and b decay vertexing is critically important for this measurement, can any variation of the SiD vertex detector design improve sensitivity in the $H \to b\bar{b}, \tau^+\tau^-$ channels?
- Can τ reconstruction be further optimized by exploiting particle flow? What is the improvement in the τ sample purity? What limits di-tau mass resolution?
- How does hadronic calorimeter leakage impact the separation of Z/H? Can it be mitigated at higher $\sqrt{s}$ required for double Higgs production?

These questions can be investigated with a combination of full and fast simulation of the SiD detector, both of which have been made available by the SiD consortium.

Conclusions

Measuring the Higgs self-coupling λ_{hhh} is a critically important part of the program of high energy particle physics at future colliders. The ILC is an excellent environment for this measurement, and the SiD detector, with its precision vertexing and jet energy resolution, is the right instrument for its realization. Further conclusions will be elaborated as this study advances.

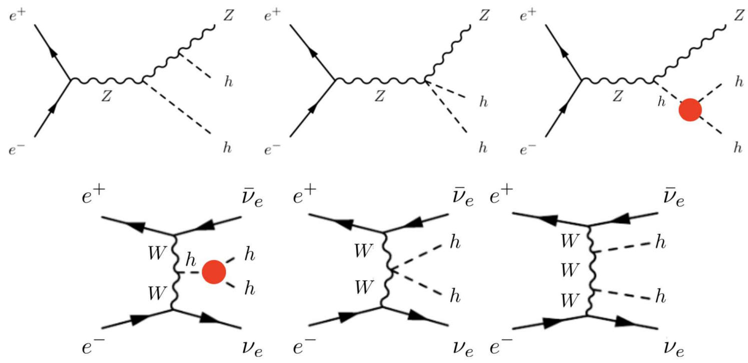

Figure 1: Feynman diagrams for double Higgstrahlung (top) and double WW fusion (bottom) at e^+e^- colliders. Red dots indicate the triple Higgs self-coupling. Taken from [3].

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